Discriminating a Gravitational Wave Background from Instrumental Noise using Time-Delay Interferometry

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Reference:

[1] **M.Tinto**, *Phys. Rev. D*: **58**, 102001 (1998)
[2] **M. Tinto & J.W. Armstrong**, *Phys. Rev. D*: **59**, 102003, (1999)
[3] **J.W. Armstrong, F.B. Estabrook, & M. Tinto**, *Ap. J.*, 527: 814-826, 1999 December 20
[4] **F.B. Estabrook, M. Tinto, & J.W. Armstrong**, Phys. Rev. D: In press.
[5] **M. Tinto, J.W. Armstrong, & F.B. Estabrook,** In Preparation.

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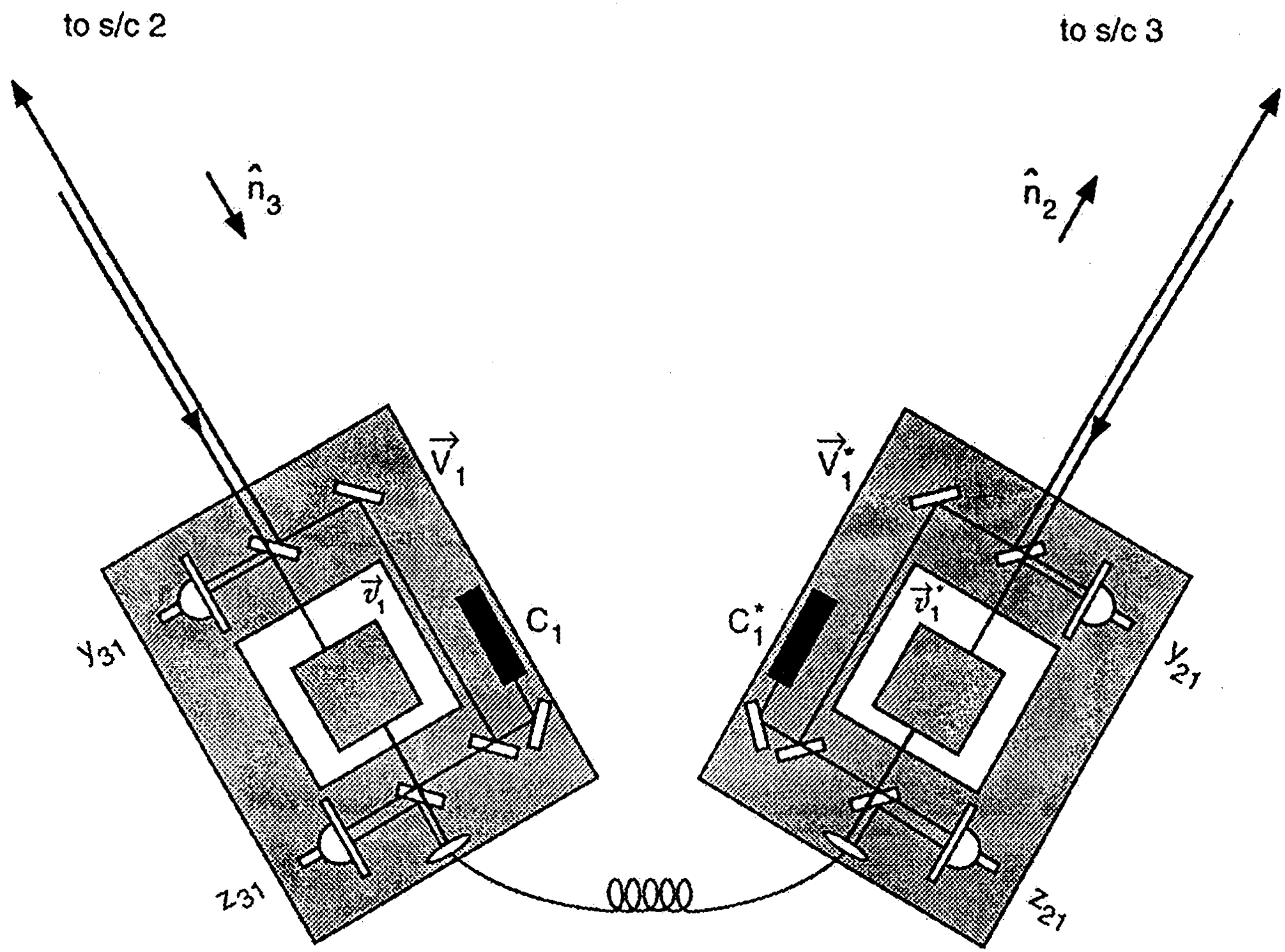
EARTH vs SPACE BASED INTERFEROMETERS

- Earth-based interferometers have arm-lengths essentially equal. This is in order to directly remove laser frequency fluctuations at the photodetector, where the two beams interfere.
- Unlike ground-based detectors, LISA can not maintain precise arm-length equality.
- Time-of-flight of laser signals and gravitational waves throughout the apparatus are important ($\lambda_{GW} <= L$)
- Spacecraft cannot be isolated, but incorporate drag-free proof masses to allow monitoring of spacecraft accelerations.

Time-Delay Interferometry

- In our previous work [3] we treated time-delay gravitational wave interferometry with three spacecraft, each idealized as moving almost inertially and rigidly carrying optical benches.
- Each spacecraft transmits laser signals to the other two, and using its laser as a local oscillator, measures the frequencies of the laser beams received from the other two.
- In [2, 3] we presented and analyzed combinations of these data streams which eliminated the laser frequency fluctuations (the dominant noise source!), while retaining the gravitational wave signal.
- We have generalized the results derived in [3] to the actual drag-free configuration envisaged for LISA.


to s/c 2
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$\hat{n}_3$
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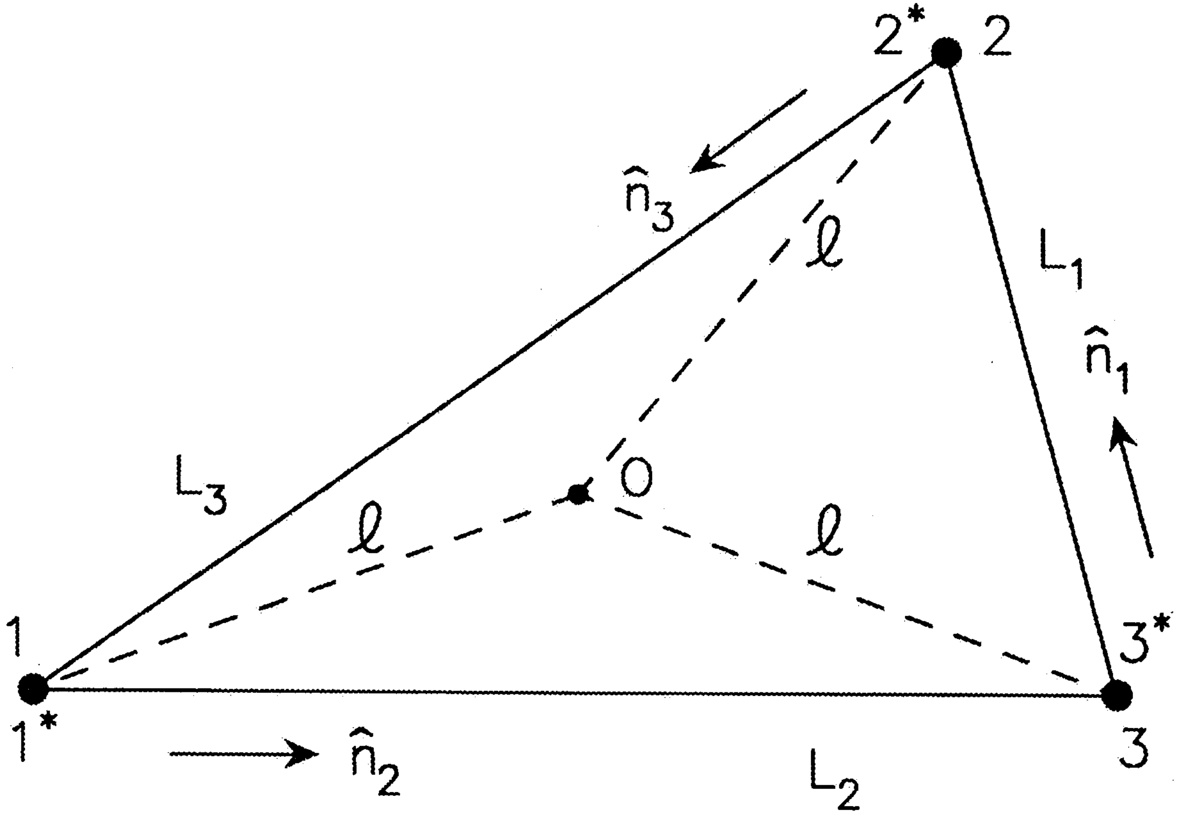
C_1
C_1^*
y_{31}
z_{31}
y_{21}
z_{21}



2*
2
$\hat{n}_3$
ℓ
L_1
$\hat{n}_1$
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0
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ℓ
1
3*
1*
$\hat{n}_2$
3
L_2

<u>Time-Delay Interferometry (Cont.)</u>

- <u>In summary</u>: there are 6 optical benches, 6 lasers, and a total of 12 Doppler time series observed.

- The 6 beams exchanged between distant spacecraft contain the information about the GW signal (y_{ij}); the other 6 signals (z_{ij}) are for comparison of the lasers and relative optical bench motions within the spacecraft.

One-Way Responses

- y_{21} (t) = Doppler measured at spacecraft # 1, with transmission at spacecraft # 3; $y_{21,3} = y_{21}(t - L_3)$
- z_{21} (t) = Doppler measured at bench # 1*, with transmission at bench # 1; z_{31} (t) = Doppler measured at bench # 1, with transmission at bench # 1*.

$$y_{21}(t) = C_{3,2} - \vec{n}_2 \cdot \vec{V}_{3,2} + 2\,\vec{n}_2 \cdot \vec{v}_1{}^* - \vec{n}_2 \cdot \vec{V}_1{}^* - C_1{}^* + y^{gw}{}_{21}(t) + y^{shot}{}_{21}(t)$$
$$z_{21}(t) = C_1 + 2\,\vec{n}_3 \cdot (\vec{v}_1 - \vec{V}_1) + \rho_1 - C_1{}^*$$

$$y_{31}(t) = C^*{}_{2,3} + \vec{n}_3 \cdot \vec{V}^*{}_{2,3} - 2\,\vec{n}_3 \cdot \vec{v}_1 + \vec{n}_3 \cdot \vec{V}_1 - C_1 + y^{gw}{}_{31}(t) + y^{shot}{}_{31}(t)$$
$$z_{31}(t) = C_1{}^* - 2\,\vec{n}_2 \cdot (\vec{v}_1{}^* - \vec{V}_1{}^*) + \rho_1 - C_1$$

- Eight other relations are obtained by cyclic permutation of the indices in the equations above.

Data Combinations which Eliminate Laser noise and Optical Bench Motions

- Unequal-arm Interferometer response: **X**

$$X = y_{32,322} - y_{23,233} + y_{31,22} - y_{21,33} + y_{23,2} - y_{32,3} + y_{21} - y_{31}$$
$$+ 1/2\, [-z_{21,2233} + z_{21,33} + z_{21,22} - z_{21}]$$
$$+ 1/2\, [+z_{31,2233} - z_{31,33} - z_{31,22} + z_{31}]$$

- The remaining noise terms due to the proof-mass motion, $\vec{v}_i$, $\vec{v}_i^*$, are:

$$X^{\text{proof mass}} = \vec{n}_2 \cdot (- \vec{v}^*_{1,2233} + \vec{v}^*_{1,22} - \vec{v}^*_{1,33} + \vec{v}^*_{1} + 2\, \vec{v}_{3,233} - 2\, \vec{v}_{3,2})$$
$$+ \vec{n}_3 \cdot (- \vec{v}_{1,2233} - \vec{v}_{1,22} + \vec{v}_{1,33} + \vec{v}_1 + 2\, \vec{v}^*_{2,223} - 2\, \vec{v}^*_{2,3})$$

Data Combinations which Eliminate Laser noise and Optical Bench Motions (Cont.)

- Sagnac Interferometer: ξ

$$\xi = y_{32,2} - y_{23,3} + y_{13,3} - y_{31,1} + y_{21,1} - y_{12,2}$$
$$+ 1/2\,[-z_{13,21} + z_{23,12} - z_{21,23} + z_{31,23} - z_{32,13} + z_{12,13}]$$
$$+ 1/2\,[-z_{32,2} + z_{12,2} - z_{13,3} + z_{23,3} - z_{21,1} + z_{31,1}]$$

- The remaining noise terms due to the proof-mass motion, v_i, v_i^*, are:

$$\xi^{\text{proof mass}} = \vec{n}_1 \cdot (\vec{v}_{2,2} - \vec{v}_{2,13} + \vec{v}^*_{3,3} - \vec{v}^*_{3,21})$$
$$+ \vec{n}_2 \cdot (\vec{v}_{3,3} - \vec{v}_{3,21} + \vec{v}^*_{1,1} - \vec{v}^*_{1,23})$$
$$+ \vec{n}_3 \cdot (\vec{v}_{1,1} - \vec{v}_{1,23} + \vec{v}^*_{2,2} - \vec{v}^*_{2,13})$$

Conclusions

- We have shown that there exist several linear combinations of the twelve data that minimize the gravitational wave signal.
- In the frequency region of interest they all display the same sensitivity as the Sagnac Interferometer ξ.
- It is therefore possible to assess the magnitude of the noise sources affecting LISA.
- This will allow us to measure a gravitational wave background in the frequency region of interest.